Integrated Nutrient Management Practices for Sustainable Chickpea: A Review

Abstract

Chickpea (*Cicer arietinum* L.) is a vital legume crop which considerably contributes to the nutritional security of millions. Sustainable production of chickpea requires optimizing nutrient management practice to improve productivity while sustaining soil health. Integrated Nutrient Management (INM) is an approach by which chemical fertilizers, organic manures, and bio-fertilizers are applied judiciously to meet balanced nutrient supply. This review collates recent research on INM strategies in chickpea, discussing their effect on yield, soil fertility, and environmental sustainability.

Keywords: chickpea, chemical fertilizer, organic manures, bio-fertilizer

Introduction

Chickpea (*Cicer arietinum* L.) ranks as one of the world's most vital leguminous crops in terms of its high protein content and its ability to enrich soil fertility through biological nitrogen fixation (Zhang *et al.,* 20240. Millions regard it as a staple source of dietary protein, especially in developing countries; the crop is used in various traditional dishes, animal feed, and even as raw material for food processing industries (Wu *et al.*, 2014; Nadathur *et al.*, 2016). Its adaptability to different agro-climatic regions and low water requirement make it an essential crop for sustainable agriculture (Roy *et al.*, 2023). Chickpea also plays a critical role in crop rotation systems because of its symbiotic relationship with nitrogen-fixing bacteria (*Rhizobium*), which minimizes the dependency on synthetic nitrogen fertilizers (Kebede, 2021). This natural nitrogen fixation not only enriches the soil fertility but also helps the subsequent crops through the residual nitrogen pool available in the soil (Meena *et al.*, 2020).

Despite these benefits, chickpea productivity is severely hindered by the following factors:

Permanent monoculture and agricultural lands overuse result in soil nutrient impoverishment and decreased fertility (Bisht *et al.*, 2020). It excessive and unbalanced application have resulted in the degradation of the health of the soil system, imbalances in available nutrients, and environmental pollution in forms including greenhouse gases and water pollution (Lal, 2009). Erratic rainfall, increasing temperature, and limited availability of organic amendments further stressed the production systems of chickpea (Gupta, & Verma, 2020; Chandra, 1980). To overcome these problems, sustainable agricultural practices must be encouraged. INM is one of the promising approaches to efficiently increase nutrient use efficiency with maintaining soil health (Ahmad, & Khan, 2020; Wu, and Ma, 2015). INM incorporates the combined use of chemical fertilizers, organic manures, bio fertilizers, and micronutrients in balanced and continuous supplies to ensure the proper accomplishment of all agronomic activities (Chaubey *et al.*, 2023). This practice not only increases crop productivity but also enhances soil organic matter contents, stimulates microbial activity, and reduces its impacts on the environment (Mohammadi *et al.*, 2011).

This review provides an analysis of all the above-mentioned constituents of INM and their particular involvement in chickpea crop production. It outlines how the integration of different nutrient sources can significantly contribute to sustaining chickpea yields, enhancing soil fertility, and being environmentally friendly. However, this review consolidates existing knowledge and practical information to be a useful source for policymakers, researchers, and farmers aiming to adopt sustainable nutrient management practices into chickpea cultivation systems.

Table 1: Several researchers have conducted studies on integrated nutrient management in chickpea, as listed below.

Sr.No	Research topic	Researchers
1.	Integrated use of vermicompost and inorganic fertilizer in chickpea. *Annals of plant physiology*.**17**(2):205-206.	**Asewar *et al.* (2003)**
2.	Effect of row ratio and fertility level on growth, productivity, competition and economics in chickpea+ funnel intercropping system under scarce moisture condition. Journal of food legumes Volume 24 (3):211-214 ISSN: 0976-2434	**Awasthi *et al.* (2011)**
3.	Effect of Organic and Inorganic Fertilizers on *Growth, Yield and Yield Components of Chick Pea (Cicer arietinum*) and Enhancing Soil Chemical Properties on Vertisols at Ginchi, Central Highlands of Ethiopia. *Journal of Biology, Agriculture and Healthcare* Vol.7, No.23,2224-3208	**Chala Girma (2017)**
4.	Effects of Biofertilizer with and without Molybdenumon Growth and Seed Yield of Chickpea under DoonValley of Uttarakhand *Current Journal of Applied Science and Technology* 39(**15**): 133-139	**Chandra Girish (2020)**
5.	Evalution of Rhizobium Efficiency in Chickpea through Boron Management. BhartiyaKrisiAnusandhanPatrikaVol**31** No 3; PP: 181-186	**Das *et al.* (2016)**
6.	Effect of integrated nutrient management productivity and quality of chickpea (*Cicer arietinum* .L*)* Ph.D. Thesis CSAUA&T (Kanpur)	**Anil Kumar (2018-2019)**
7.	Effect of farm yard manure, phosphorus and sulphur on yield parameters, yield, nodulation, nutrient uptake and quality of chickpea (*Cicer arietinum* L.) *Journal of Applied and Natural Science* 8 (2): 545 - 549	**Das *et al. (*2016)**
8.	Effect of integrated nutrient management and drought mitigating practices on performance of rainfed chickpea (*Cicer arietinum) Indian Journal of Agricultural Sciences* **87** (3): 301–5	**Dewangan *et al.* (2017)**
9.	Combined effect of bio fertilizer and micronutrients on fertility, growth and productivity of chickpea. *Journal of Pharmacognosy and Phytochemistry*, *8*(6), 22576-2579.	**Anil *et al.* (2020)**
10.	Response of fertility levels and biofertilizers on growth and yield attributes quality of chickpea. *Asian Journal of Soil Science and Plant Nutrition*, *10*(2), 358-365.	**Jain *et al.* (2024)**
11.	Influence of nitrogen fixing and phosphorus solubilizing bacteria on the nodulation, plant growth, and yield of chickpea. *Journal of Plant Nutrition* **31**(1) : 157-171.	**Elkoca *et al. (*2008)**
12.	Effect of different organic and inorganic fertilizers on nutrient content, uptake and quality of chickpea. *Journal of Pharmacognosy and Phytochemistry*, *9*(6), 2073-2079.	**Anil *et al.* (2020)**

13.	Effect of integrated nutrient management on growth and yield of maize-chickpea cropping system. *Journal of Soils and Crops*, **18**(2) : 392-397.	**Gable *et al.* (2008)**
14.	Effect of potassium level and foliar application of nutrient on growth and yield of late sown chickpea *(Cicerarietinum L.). Environment and Ecology.**32** (1A):273-275*	**Ganga *et al.* (2014)**
15.	Nutrient balance under INMS in sorghum-chickpea cropping sequence.*Indian Journal of Agricultural Research*, **41**(2) : 137-141.	**Gawai *et al.* (2007)**
16.	Vermicompost as a soil supplement to relieve the effects of low-intensity drought stress on chickpea yield. Acta Horticulture (1018):219-226.	**Gholipoor *et al.* (2014)**
17.		
18.	Studies on organic and inorganic sources of nutrient application in cotton – chickpea cropping sequence. *Omonrice* 18: 121-128.	**Gudadhe *et al.* (2011)**
19.	Effect of bio-fertilizers and foliar spray of urea on symbiotic traits, nitrogen uptake and productivity of chickpea, Journal of food legumes, 24 (2), 155-157, 2011.	**Gupta *et al.* (2011)**
20.	Effect of Farmyard Manure (FYM),Vermicompost and Chemical Nutrients on the growth and yield of Chickpea. *(Cicer arietinum L.)International Journal of Agriculture Research*, 7:93-99.	**Guriqbal *et al.* (2012)**
21.	Effect of Integrated Nutrient Management Modules on Nutrient Uptake, Quality and Economics of High Yielding Varieties of Chickpea (*Cicer arietinum* L.) under Late Sown Condition. *International Journal of Agriculture Sciences, ISSN: 0975-3710 & E-ISSN*: 0975-9107, 10: (24), 7675-7677	**Harikesh *et al.* (2018)**
22.	Effect of vermicompost fertilizer on photosynthetic characteristics of chickpea (*Cicer arietinum* L.) under drought stress, *Photosynthetica*,**54**(1),87-92.	**Hosseinzadeh *et al.* (2016)**
23.	Effect of organic and inorganic N fertilizer on growth and yield of chickpea (*Cicer arietinum* L. grown on sandy soil using 15 N Tracer. Bangladesh J. Bot. 46**(1**): 155-161	**Ismail *et al.* (2017)**
24.	Direct and residual effect of vermicompost, biofertilizers and phosphorus on soil nutrient dynamics and productivity of chickpea-fodder maize sequence. *J. Sustanable Agric.* 27 : 41-54.	**Jat *et al.* (2006)**
25.	Growth and nutrient uptake of chickpea (*Cicer arietinum* L.) as influenced by bio-fertilizers and phosphorus nutrition. *Crop Research (Hisar)*, **25**(3) : 410-413.	**Jain, and Pushpendra (2003)**
26.	Effect of FYM and biofertilizer in conjunction with inorganic fertilizer on growth, yield and profit of chickpea (*Cicer arietinum* L.). *Plant Archives*, **5**(2): 609-612.	**Kedar *et al.* (2005)**
27.	Efficiency of biofertilizers in increasing the production potential of cereals and pulses: A review Journal of Pharmacognosy and Phytochemistry.; 8(2): 183-188	**Khanna *et al.* (2019)**
28.	Effect of phosphorus, sulphur and PSB on quality components and nutrient uptake in chickpea. *Annals of Plant Physiology*, **20**(1): 78-81. J. M.	**Kharche *et al.* (2006)**
29.	Growth of yield attributes and yield of summer blackgram (*Vigna mungo* L.) as influenced by FYM, Phophorus and sulphur. *An International quarterly journal of Environmental Sciences.* Special issue, Vol.(4): 429-433	**Kokani *et al.* (2014)**
30.	Quality enhancement in chickpea mediated through integrated nutrient management. *Journal of Pharmacognosy and Phytochemistry*; 7(4): 3212-3216	**Kumar *et al.* (2018)**
31.	Effect of integrated nutrient management (INM) on productivity and profitability of chickpea *(Cicer arietinum L.) International Journal of Chemical Studies*; 6**(6):** 1672-1674	**Kumar *et al.* (2018)**
32.	**).** Effect of Biofertilizer and Micronutrients on Yield of Chickpea *Int.J.Curr.Microbiol.App.Sci* (2019) 8(1): 2389-2397	**Thomas *et al.* (2019)**

33.	Residual Effect of Manure and Fertilizer on Growth, Yield of Chickpea and Soil Nutrient Status under Maize-Chickpea Cropping System. *Int.J.Curr.Microbiol.App.Sci.* 9(4): 2940-2945.	**Lakum *et al.* (2020)**
34.	Impact of phosphorus and iron on protein and chlorophyll content in chickpea *(Cicer arietinum L.) Lergume research* **38** (4):588.	**Mathur *et al.* (2015)**
35.	Evalution of spaced channel irrigation method and nutrient management in chickpea (*Cicer arietinum* L.). *Environment and Ecology*.**27** (1):49-52.	**Paraye *et al.* (2009)**
36.	Effect of soil and foliar application of zinc and Boron on growth, yield and micro nutrient uptake of Chickpea *Journal of Pharmacognosy and Phytochemist*ry 9(4): 3356-3360	**Rathod *et al.*, (2020)**
37.	Effect of biofertilizers, *Rhizobium* & phosphate in combination of different level of Ca, Mg & S on the productivity of chickpea (*Cicer arietinum* L.) cultivar Avrodhi. *Journal of Plant Development Sciences*, **3**(3/4) : 243-245	**Nazo *et al.* (2011)**

2. Constituents of INM for Chickpea

2.1. Chemical Fertilizers

Chemical fertilizers provide immediate availability of macronutrients necessary for full expression of growth and development of plants. In chickpea, nitrogen (N), phosphorus (P), and potassium (K) are most crucial (Yahaya *et al.*, 2023).

Nitrogen (N): Although chickpea is a leguminous crop capable of fixing atmospheric nitrogen through symbiotic associations with Rhizobium bacteria, a small starter dose of nitrogen (around 20–25 kg/ha) is often recommended (Abdula, 2013). This provides an initial boost for early vegetative growth until the nitrogen-fixing nodules become fully functional (Hailemichael, 2020).

Phosphorus (P): Phosphorus is pivotal for root development, nodulation, and energy transfer processes within the plant (Gebremedhin, 2016). Adequate phosphorus availability enhances nodulation efficiency and supports the fixation of atmospheric nitrogen (Mitran *et al.*, 2018). Research suggests that phosphorus application rates between 20–40 kg/ha are optimal, depending on soil phosphorus levels (Umar *et al.*, 2020). The application of phosphorus is often done using single super phosphate (SSP) or di-ammonium phosphate (DAP) (Admasu, 2019).

Potassium (K): Potassium promotes plant strength, boosts biotic and abiotic stresses tolerance and seed quality (Wang *et al.*, 2013). Based on the soil test, application rate for potassium differs. But typically 20–30 kg/ha would be sufficient for the cultivation of chickpea (Hasanuzzaman *et al.*, 2018).

Balanced fertilization using chemical fertilizers is aimed at achieving an optimal nutritional balance without risking nutrient imbalances or the degradation of soils (Cissé, 2007).

2.2 Organic Manures

Organic manures are natural sources of nutrients that improve soil health, enhance microbial activity, and provide slow-releasing nutrients to the crop (Shaji *et al.*, 2021). Some common organic manures used in chickpea production include farmyard manure (FYM), compost, and vermicompost (Akash *et al.,* 2022 ; Jain, *et al.*, 2021).

Farmyard Manure (FYM): FYM is a rich source of organic matter and nutrients such as nitrogen, phosphorus, and potassium in organic forms (Antil, and Singh, 2007). Application rates of 5–10 t/ha of FYM have been shown to significantly improve soil structure, water-holding capacity, and nutrient availability, leading to increased chickpea yields (Yadav, 2023).

Compost: Compost is prepared from decomposed plant and animal residues (Sayara *et al.*, 2020). It enriches the soil with nutrients and beneficial microbes, contributing to better nutrient recycling and improving the soil's organic carbon content (Bhunia *et al.,* 2021).

Vermicompost: Vermicompost is a nutrient-rich organic amendment produced through the action of earthworms (Walia and Kaur 2024). It contains readily available forms of nitrogen, phosphorus, and other micronutrients, promoting early plant growth and sustained nutrient release (Shrivastav *et al.*, 2020).

Organic manures in combination with chemical fertilizers improve nutrient use efficiency and soil fertility. This is one of the sustainable systems of chickpea production (Ramaiyan *et al.,* 2023).

2.3. Bio-fertilizers

Bio-fertilizers are the microbial inoculants which make the nutrients available to the plants through biological means (Sowmya *et al.,* 2024). In chickpea, Rhizobium and phosphate-solubilizing bacteria (PSB) are the most important bio-fertilizers (Sharma, *et al.,* 2021).

Rhizobium: It is a symbiotic bacterium which, by association with roots of chickpea, transforms into root nodules (Rashid *et al.,* 2015), which allow atmospheric nitrogen to be captured and made available for absorption by the plant (Carranca, 2013). Its inoculation has improved its ability to fix nitrogen, enhanced plant growth, and increased seed production by 15–25% (Patel, and Sharma, 2019) and (Fred *et al.,* 2002). Proper inoculation involves treatment of seeds prior to sowing with a Rhizobium culture that helps effectively colonize and nodulate their roots (Gebremedhin, 2016).

Phosphate-Solubilizing Bacteria (PSB): PSB increases the solubility of insoluble phosphorus compounds in soil, making phosphorus more accessible to plants. This minimizes the application of chemical phosphorus fertilizers and maximizes overall phosphorus use efficiency.

Applying Rhizobium and PSB as seed or soil inoculant will optimize nutrient uptake, reduce costs of fertilizer, and improve the sustainability of chickpea production (Ramaiyan *et al.,* 2023).

2.4. Micronutrients

Although micronutrients are required in very small amounts (Fouda *et al.,* 2017), they are very important for plant growth and physiological processes (Tripathi *et al.,* 2015) and Das, & Roy, 2019). Deficiencies of zinc and boron are very common in chickpea and can affect productivity and seed quality very significantly (Muhammed, 2023).

Zn: This element plays a critical role in chickpea for enzyme activation, protein synthesis, and regulation of growth (Wang *et al.,* 2021; Ullah *et al.,* 2020). Zinc sulfate is one of the most frequently used sources applied at a rate of 20–25 kg/ha for soil application (Jalal *et al.,* 2022).

Foliar sprays with 0.5% zinc sulfate during flowering and pod-setting have been reported to enhance seed quality and yield (Singaravel *et al.*, 2022)).

Boron (B): Boron is involved in cell wall synthesis, membrane integrity, and pollen tube formation. The deficiency results in less flowering and poor pod formation (Blevins, and Lukaszewski, 1998). Borax applied as a soil amendment at 1–2 kg/ha or foliar spray at 0.1–0.2% is effective for alleviating boron deficiency (Raj, and Raj, 2019).

Chickpea is a direct source of dietary protein and constitutes an important crop in cropping systems mainly because it can fix the atmospheric nitrogen (Grasso *et al.*, 2022). However, these intensive cultivations, and declining soil fertility (Gruhn, *et al.*, 2000) increased dependence on chemical fertilizers have led to the emergence of sustainable nutrient management approaches (Wu, and Ma, 2015), and integrated nutrient management has emerged as the viable solution to these emerging challenges (Kumar, and Choudhary, 2018). This review looks into various aspects of INM components and their contributions in chickpea production systems in full expansion.

3. INM Strategies in Chickpea Production

INM involves the strategic combination of chemical fertilizers, organic manures, bio-fertilizers, and micronutrients to ensure balanced nutrient availability for crops (Nakade *et al.*, 2021). INM strategies in chickpea cultivation are aimed at optimizing nutrient use efficiency (Singh, & Kumar, 2022) and (Choudhary *et al.*, 2020), enhancing soil fertility, and promoting sustainable production (Meena *et al.*, 2019).

3.1. Combined Use of Fertilizers and Manures

The integration of organic manures with chemical fertilizers results in a synergistic effect ensuring balanced nutrient supply throughout the crop growth cycle (Subhash, 2021). Organic manures, such as farmyard manure (FYM), vermicompost, and compost, improve soil physical, chemical, and biological properties (Singh *et al.*, 2020). Chemical fertilizers, in turn, provide immediately available nutrients for the plants (Pahalvi *et al.*, 2021).

For instance, the application of 50% RDF in combination with 5 t/ha of FYM has been found to increase chickpea yield by up to 20% (Mohan, 2021). This approach benefits both the crop and the soil in several ways:

Organic manures slowly release nutrients over time, complementing the immediate nutrient supply from chemical fertilizers (Timsina, 2018). Manures enhance soil organic matter content, water-holding capacity, and microbial activity, which are critical for long-term soil health (Gurmu, 2019; Singaravel and Seenivasan, 2024). Reducing the reliance on chemical fertilizers lowers production costs for farmers and minimizes the environmental impact of excessive fertilizer use (Chien *et al.*, 2009).

Research demonstrates that such combinations not only enhance crop productivity but also sustain soil fertility, making it a sustainable practice for chickpea production systems (Korbu *et al.,* 2020).

3.2. Bio-fertilizers Role in Efficiency

Bio-fertilizers like Rhizobium and PSB have an important role in nutrient cycling and improving nutrient availability to chickpea plants (Singh *et al.*, 2024; Alamzeb *et al.*, 2024). The interaction of microbial inoculants with plant roots triggers biological processes such as nitrogen fixation and phosphorus solubilization (Alori *et al.,* 2017).

Rhizobium: It shows symbiotic association with the roots of chickpea, fixes atmospheric nitrogen, and converts it to a form assimilable by the plant (Rashid *et al.,* 2015; Djouider *et al.,* 2022). Seed inoculation with culture of Rhizobium has been claimed to enhance efficiency of nodulation and nitrogen fixation to the tune of 30% more yield (Abd-Alla *et al.,* 2023).

Phosphate-Solubilizing Bacteria (PSB): PSB enhances the solubilization of insoluble phosphate compounds in the soil, making phosphorus available for plant uptake (Bargaz *et al.,* 2021). This reduces dependency on chemical phosphorus fertilizers and ensures effective utilization of phosphorus (Schröder *et al.,* 2021).

It enhances nutrient use efficiency and reduces input costs with a decreased application of chemical fertilizers, thus improving environmental sustainability (Panhwar *et al.,* 2019). Various studies indicate that such a combination promotes growth in plants, increases nodulation, and maintains yields at the same level of soil fertility (Ghosh *et al.,* 2007; Meena, *et al.,* 2022).

3.3. Site-Specific Nutrient Management (SSNM)

Site-Specific Nutrient Management (SSNM) is a precision approach that makes nutrient application according to the need of a field, based on the soil test results, crop requirements, and local agro-climatic conditions (Sarma *et al.,* 2024; Swami *et al.,* 2009). By addressing the nutrient variability across a field, SSNM ensures optimal resource use and improves nutrient recovery efficiency (Sarkar *et al.,* 2017).

Regular testing of soil gives critical information of nutrient status in the field (Hodges, 2010). This helps in the precise use of nutrients to correct specific deficiencies (Römheld, 2012). SSNM also emphasizes balanced use of chemical fertilizers, organic manures, and bio-fertilizers for crop nutrient need, maintaining soil health also (Singh, 2024). SSNM usually employs high-end technologies such as GIS, remote sensing, and mobile apps to determine nutrient application at the micro-level.

In chickpea cultivation, the adoption of SSNM has been highly beneficial in terms of yield and quality, saving wastage of fertilizers, and improving soil fertility (Choudhary *et al.,* 2018). By matching nutrient supply to crop demand, SSNM optimizes the efficiency of nutrient use and promotes sustainable agriculture.

These strategies, in aggregate, highlight the need to integrate various nutrient sources for sustainable productivity in chickpea production without compromising viability on environmental and economic terms.

4. Role of INM in Soil Health and Environment

In addition to increasing crop production, Integrated Nutrient Management (INM) positively impacts improving soil health as well as reducing environmental deterioration (Wu *et al.,* 2015). Combined organic, inorganic, as well as biological sources of nutrients with INM allow for sustainable agricultural practices wherein productivity is coupled with eco-responsibility (Selim, 2020).

4.1 Soil Fertility Improvement

INM practices play an essential role in maintaining the long-term fertility of soil by enhancing various physical, chemical, and biological characteristics of the soil (Nakade *et al.*, 2021).

Organic matter of the soil

It adds the organic manures, like farmyard manure (FYM), compost, and vermicompost, in the INM, increasing the content of organic matter of the soil (Chahal *et al.*, 2020). Organic matter, therefore, becomes a reservoir for slowly releasing the nutrients to crops and improving structure, water-holding capacity, and aeration (Ali *et al.*, 2019; Prabhu *et al.*, 2021).

Microbial Activity

Organic amendments and bio-fertilizers enhance soil microbial growth and activity, playing a crucial role in nutrient cycling (Singh *et al.*, 2020). For example, phosphate solubilizing bacteria increases phosphorus availability, Rhizobium facilitates N fixation in legumes as chickpea, which also supports processes such as decomposition and nutrient mineralization due to increasing microbial diversity (Kebede, 2021).

Nutrient Cycling

INM maximizes the recycling of nutrients within the soil system. The application of organic residues and the activity of bio-fertilizers ensure that all the essential nutrients like nitrogen (N), phosphorus (P), and potassium (K) are cycled and made available to the plants (Imran, 2024). This reduces the nutrient loss and maintains soil fertility during successive crop cycles.

Crop Rotation with Legumes

Legumes like chickpea in cropping systems increase biological fixation of nitrogen in the soils and, thus, create increased levels of soil nitrogen (Kebede, 2021). Legumes generally enrich the residue left by such crops, which is more easily utilized by subsequent crops that reduce the application of synthesized fertilizer nitrogen (Kakraliya *et al.*, 2018).

In totality, INM can sustainably manage soil fertility toward enhancing a healthier soil to better support long-term agriculture productivity (Rolaniya *et al.*, 2023).

4.2 Environmental Sustainability

INM significantly contributes to environmental sustainability by addressing the negative effects of over-reliance on chemical fertilizers and promoting eco-friendly farming practices (Raj *et al.*, 2024). These include:

Reducing Greenhouse Gas Emissions

The overuse of chemical fertilizers, especially those containing nitrogen, leads to massive greenhouse gas emissions in the form of nitrous oxide (N_2O) (Xuejun *et al.*, 2011). By integrating organic and bio-fertilizer components, INM minimizes the reliance on synthetic fertilizers (Choudhary *et al.*, 2018), which would otherwise increase the carbon footprint of agricultural activities.

Minimization of Nutrient Leaching and Runoff

Using chemical fertilizers at large quantities leads to leaching into the ground water as well as run-off in water bodies leading to polluting and eutrophying (Smith *et al.*, 2013). INM encourages a balanced utilization of nutrients, thus minimizing this risk factor (Singh, 2020). Organic manures ensure that the nutrient in soil is retained with no chances of loss to the environment (Singh *et al.*, 2022).

Promotion of Eco-Friendly Farming Practices

The environmental impact of the production and application of synthetic fertilizers is minimized by the application of bio fertilizers such as Rhizobium and PSB (Ali *et al.*, 2019; Shah and Wu, 2019). Bio fertilizers are replenish able, biodegradable, and nontoxic to soil and water environments (Chaudhary *et al.*, 2020).

Conservation of Biodiversity

INM practices are helpful in maintaining soil biodiversity by stimulating microbial populations and a healthy environment for beneficial microorganisms (Verma *et al.*, 2023). This helps to maintain ecological balance and agricultural ecosystems against pests and diseases.

Improved Resource Use Efficiency

Through the application of nutrients according to crop demand and soil condition, INM optimizes the inputs, thus preventing wastage and conserving natural resources, such as energy and water (Wu, and Ma, 2015).

These mechanisms support a sustainable agricultural system, which does not only improve productivity but also protects natural resources and decreases the environmental impacts of agriculture.

5. Challenges and Future Directions

In spite of its proven benefit in ensuring sustainable chickpea production, several factors hinder its full adoption in practice (Korbu *et al.*, 2020). The challenges originate from restricted dissemination of information, restricted availability of resources, and uneven performance by some of the INM components. All these areas will have to be targeted through focused research, policy interventions, and integration of relevant technology so that its complete potential may be exploited (Czajkowski, *et al.*, 2001).

5.1. Challenges to the Adoption of INM

Limited Dissemination of Information

Most farmers are unaware of the principles and benefits of INM. Low adoption rates are partly due to the lack of access to extension services, training programs, and informational resources (Sarkar, *et al.*, 2022) and (Jha *et al.*, 2024). Small and marginal farmers have less incentive to adopt INM because they are more focused on immediate returns rather than long-term sustainability (Etyang, 2013).

Resource availability and accessibility

Due to limited supply, quality organic manures, bio-fertilizers, and formulations of micronutrients, especially in remote or resource-poor areas, might not be readily available (Bayu, 2020). The main constraints are associated with transportation costs, inappropriate supply chains, and the poor condition of storage facilities for those inputs.

Bio-fertilizer Variability

The efficacy of bio-fertilizers like Rhizobium and phosphate-solubilizing bacteria may vary with soil types, climatic conditions, or management practices (Abawari *et al.,* 2020). Bio-fertilizer inoculants may lose viability if improper storage or handling is made, resulting in inconsistent field responses (Khalid *et al.,* 2021).

Installation Costs and Manpower

Although INM is a cost-saver in the long term, some of the investments on organic manures, bio-fertilizers, and soil testing are much more expensive at the beginning compared to traditional fertilizer application. Manuring or compost preparation is labor-intensive and would not favor resource-poor farmers.

Policy and Institutional Gaps

Supportive policies and institutional support for the adoption of INM are lacking. The incentives in terms of subsidies for chemical fertilizers are given with no encouragement of the use of organic and bio-fertilizers (Wu, and Ma, 2015).

5.2. Future Prospects

Regional Specific INM Models

Developing region-specific models for specific agro-climatic zones, types of soil, and crops would be essential to optimizing nutrient management. These models need to be developed from the resources available in a particular region and should solve regional-specific problems, making them more applicable to the farmers.

The Integration with Precision Farming Technologies

INM integrated with precision agriculture technologies will transform nutrient management in chickpea cultivation (Reddy, and Naik, 2020). Tools like GIS, remote sensing, and drone technology can help in site-specific nutrient management, improving resource use efficiency and reducing wastage. Mobile applications and decision-support systems can provide farmers with real-time recommendations on nutrient application.

Improving Bio-fertilizer Efficiency

Research must focus on improving the performance and reliability of bio-fertilizers.

Development of multi-strain bio-fertilizers that will effectively function across a wide spectrum of soil and climatic conditions (Mazid, *et al.,* 2015). Improvement of the shelf life and viability of bio-fertilizer formulations through advanced production and packaging techniques (Sharma *et al.,* 2015). Consortium bio-fertilizer with nitrogen-fixing, phosphorus-solubilizing, and other beneficial microbes that promote holistic nutrient management (Muthusamy *et al.,* 2023). Training programs and workshops comprehensive in nature should be instituted to raise awareness of its benefits and implementation. More knowledge dissemination and skill upgrading can be done through the extension services and the use of farmer field schools.

Policy Support and Incentives

Governments and policymakers should also prioritize INM by subsidizing organic inputs and bio-fertilizers, offering incentives for soil testing, and supporting public-private partnerships in the production and distribution of inputs (Deva *et al.*, 2024). Supportive policies would make farmers move toward more sustainable practices (Wani *et al.*, 2016).

Sustainability Research and Innovation

Further research in sustainable nutrient management practices, such as integrating INM with climate-resilient crop varieties and organic farming systems, will open avenues for future improvements (Biswas *et al.*, 2024). The development of nano-fertilizers and microbial consortia also offers scope for enhancing nutrient use efficiency (Behl *et al.*, 2024).

Addressing these challenges and future opportunities can help in transforming INM into mainstream practice for sustainable chickpea production. The practice, once adopted, can help not only improve productivity but also enhance long-term soil health, environmental conservation, and food security.

6. Conclusion

INM represents a holistic and sustainable approach to increae chickpea productivity without harming the soil environment and the ecosystem. INM combines the advantages of chemical fertilizers, organic amendments, bio-fertilizers, and site-specific practices to overcome the multi-dimensional challenges of modern chickpea cultivation.

The adoption of INM ensures a balanced and continuous supply of nutrients throughout the crop growth cycle, thereby enhancing nutrient use efficiency and optimizing yields. Organic manures and biofertilizers not only contribute to nutrient availability but also improve soil structure, microbial activity, and long-term fertility. Simultaneously, judicious use of chemical fertilizers minimizes losses of nutrients, reduces the risks associated with environmental pollution, and ensures cost-effective nutrient management.

While its benefits may transcend mere agronomy, the main importance of INM lies in aligning itself with the principles of sustainable agriculture, by reducing the use of non-renewable resources, cutting greenhouse gas emissions, and adopting more ecologically sound approaches to farming. Adding the integration of site-specific nutrient management (SSNM) with precision technologies would give the full potential of INM in efficient resource utilization and tailored application according to conditions on the field.

However, challenges in the large-scale implementation of INM include limited awareness among farmers, inconsistency in the performance of bio-fertilizers, and scarce resources. The effective breakthrough for these barriers comes from focused research efforts by researchers, extension, and policy planners. Region-specific models for INM should be developed, and the biofertilizer technology should be improved in the research sector, while extension services should initially concentrate on training and awareness programs for farmers. Such subsidies and incentives could support such inputs within infrastructures to make them accessible and available.

INM allows for the possibility of getting higher chickpea productivity while keeping the soil and environmental quality intact. Through the innovative research of how it can be practically adapted into extension work and how policies can proactively adopt this, INM is seen as an opportunity towards sustainable agricultural development and towards food security in the coming decades.

Disclaimer (Artificial intelligence)

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2.

3.

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